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A review of forced convection heat transfer enhancement and hydrodynamic characteristics of a nanofluid

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A B S T R A C T

The low thermal properties of liquids have led to investigations into additives of small size (less than 100 nm solid particles) to enhance their heat transfer properties and hydrodynamic flow. To summarise the experimental and numerical studies, this paper reviews these computational simulations and finds that most of them are in agreement with the results of experimental work. Many of the studies report enhancements in the heat transfer coefficient with an increase in the concentration of solid particles. Certain studies with a smaller particle size indicated an increase in the heat transfer enhancement when compared to values obtained with a larger size. Additionally, the effect of the shape of the flow area on the heat transfer enhancement has been explored by a number of studies. All of the studies showed a nominal increase in pressure drop. The significant applications in the engineering field explain why so many investigators have studied heat transfer with augmentation by a nanofluid in the heat exchanger. This article presents a review of the heat transfer applications of nanofluids to develop directions for future work. The high volume fraction of various nanofluids will be useful in car radiators to enhance the heat transfer numerically and experimentally. Correlation equations can expose relationships between the Nusselt number, the Reynolds number, the concentration and the diameter of the nanoparticles. On the other hand, more work is needed to compare the shapes (e.g., circular, elliptical and flat tube) that might enhance the heat transfer with a minimal pressure drop.

Contents

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1. Introduction

A nanofluid is a new class of heat transfer fluids engineered by dispersing metallic or non-metallic nanoparticles with a typical size of less than 100 nm in the base fluid (e.g., water, ethylene glycol and oil). The poor thermophysical properties of liquids may have led to the use of suspended solid particles as an additive to enhance the thermal properties and improve the heat transfer characteristics of liquids. The key idea is to improve the thermal conductivity. Because the solid particles have a larger thermal conductivity than the liquids, solid particles suspended in the liquid will improve the thermal conductivity of liquid. For many years, suspensions of millimetre- or micrometre-sized solid particles have been tested to enhance the thermal conductivity of conventional fluids, but problems of sedimentation led to increased pressure drop in the flow channel, as reported by Lee et al. [1]. Recent advances in material technology made it possible to produce innovative heat transfer fluids by suspending nanometre-sized particles that change the transport and thermal properties in base fluids. A solid liquid composite materials consisting of solid nanoparticles with size not large than 100 nm suspended in liquid defined as nanofluids [2]. Nanofluids have attracted significant interest recently because of reports of the enhancement of Thermophysical properties for many industrial applications [3–7].

This review will focus mainly on the hydrodynamic and heat transfer enhancement potential of nanofluids with forced convection flow types (laminar–turbulent) and on the effect of the concentration and diameter of nanoparticles and the shape of cross sectional tubes without much detail about Thermophysical properties. Additionally, this review will give a significant plan for accurate future work.

2. Thermal properties

The thermal conductivity of ultrafine suspensions of alumina, silica and other oxides in a base fluid water was proven to increase up to 30% at a concentration by volume of 4.3% by Masuda et al. [8]. Many researchers have used the mixture relation for estimating the density and specific heat capacity [9–20] of nanofluids with

$$\rho_{nf} = \left(\frac{\phi}{100}\right)\rho_p + \left(1 - \frac{\phi}{100}\right)\rho_f \tag{1}$$

$$C_{nf} = \frac{(\phi/100)(\rho C)_p + (1-(\phi/100))(\rho C)_f}{\rho_{nf}} \tag{2}$$

The convection heat transfer coefficient doubled when adding nanoparticles suspended in water as a base fluid in a study by Choi [21]. The thermal conductivity is a significant thermal property for enhancing the heat transfer of liquids by suspending metal or non-metal as shown in Table 1.

The thermal conductivity of nanofluids has been determined experimentally [9–18], and the data of the thermal conductivity for nanofluids of metal and metal oxides, such as Al_2O_3, Fe_3O_4, TiO_2, ZnO, ZrO_2 and CuO, consist of many data points available in the literature for use in the development of the regression Eq. (3) by Sharma et al. [23]

$$k_r = \frac{k_{nf}}{k_f} = \left\{0.8938\left(1+\frac{\phi}{100}\right)^{1.37}\left(1+\frac{T_{nf}}{70}\right)^{0.2777}\left(1+\frac{d_p}{150}\right)^{-0.0336}\left(\frac{\alpha_p}{\alpha_f}\right)^{0.01737}\right. \tag{3}$$

Viscosity is another parameter that influences heat transfer and pressure drop. The experimental study of alumina and copper oxide nanofluid viscosity under ambient conditions with different volume fractions and particle diameters have been conducted by Nguyen et al. [22]. The viscosity of a water–Al_2O_3 nanofluid with particle diameters of 36 and 47 nm and with CuO solid particles of 29 nm diameters were studied by Sharma et al. [23]. The experimental data for viscosity gathered by [24–31] for up to 4% volume concentration consisted of many data points subjected to regression by [23] to obtain the following correlation:

$$\mu_r = \frac{\mu_{nf}}{\mu_f} = \left(1+\frac{\phi}{100}\right)^{11.3}\left(1+\frac{T_{nf}}{70}\right)^{-0.038}\left(1+\frac{d_p}{170}\right)^{-0.061} \tag{4}$$

3. Forced convection heat transfer in a tube

3.1. Experimental studies

The heat transfer coefficients of nanofluids were calculated from the following equations:

$$Nu = \frac{h \times d}{k} \tag{5}$$

$$h = \frac{Q}{T_w - T_f} \tag{6}$$

3.1.1. Laminar flow in a tube

Experimental results illustrated that the convective heat transfer coefficients of nanofluids varied with the flow velocity and

Table 1
Thermal conductivities of various materials [95].

Materials	Thermal conductivity at room temperature (W/m-K)
Silver	429
Copper	401
Aluminium	237
Diamond	3300
Silicon	148
Alumina	40
Water	0.61
Ethylene glycol	0.25
Motor oil	0.15

Nomenclature

$m^\bullet$	mass flow rate (kg/s)
A	area (m^2)
Cp	specific heat capacity (W/kg k)
d	diameter of tube (m)
dp	particle diameter (m)
e	height of corrugation (m)
f	friction factor
h	heat transfer coefficient (W/m^2 k)
k	thermal conductivity (W/m k)
Nu	Nusselt number ($Nu = h \times d/k$)
P	pitch of corrugation (m)
Pe	Peclet number ($Pe = Re \times Pr$)
Pr	Prandtl number ($Pr = C \times \mu/k$)
Q	heat transfer (W)
Re	Reynolds number ($Re = u \times d \times \rho/\mu$)
T	temperature (°C)
u	velocity of fluid (m/s)
Δp	pressure drop (pa)
ϕ	concentration of solid particles
μ	viscosity
ρ	density

Subscripts

av	average value
f	fluid
nf	nanofluid
r	ratio
s	solid
w	wall

volume fraction and were higher than the base fluid under the same conditions as shown in Table 2.

A hybrid nanofluid used to enhance the heat transfer and pressure drop in fully developed laminar flow through a uniformly heated circular tube was studied experimentally by Suresh et al. [32]. The nanofluid was composed of Cu–Al_2O_3 in water synthesised with a 0.1% concentration by volume. Experimental results showed a maximum enhancement of 13.56% in the Nusselt number at a Reynolds number of 1730 when compared to the Nusselt number of water. The results also showed that 0.1% Cu–Al_2O_3–water nanofluids have a slightly higher friction factor when compared to a 0.1% Al_2O_3–water nanofluid. The correlations of the Nusselt number and the friction factor were reported, and there was good agreement with the experimental data reported elsewhere. Experimental results by Yang et al. [33] illustrated the convection heat transfer coefficient of graphite nanoparticles dispersed in a liquid for laminar flow in a horizontal tube heat exchanger. A study of laminar flow convective heat transfer of alumina nanoparticles in water with a constant surface temperature and various volume fractions was performed by Heris et al. [34]. The schematic of the experimental setup is shown in Fig. 1. The experimental results showed that the heat transfer coefficient of nanofluids increases with the Peclet number as well as with the nanoparticle concentration. An experimental study of convective heat transfer of de-ionised water at steady state with a low volume concentration of 0.003% of suspended CuO nanoparticles was conducted by Asirvatham et al. [35]. The effect of the mass flow rate ranging from (0.0113 kg/s to 0.0139 kg/s) and the effect of the inlet temperature at 100 °C and 170 °C on the heat transfer coefficient were also studied. The results showed the enhancement of convective heat transfer compared with other papers. On the other hand, the governing equations were simulated in parallel with the experimental work and the results of comparison showed good agreement.

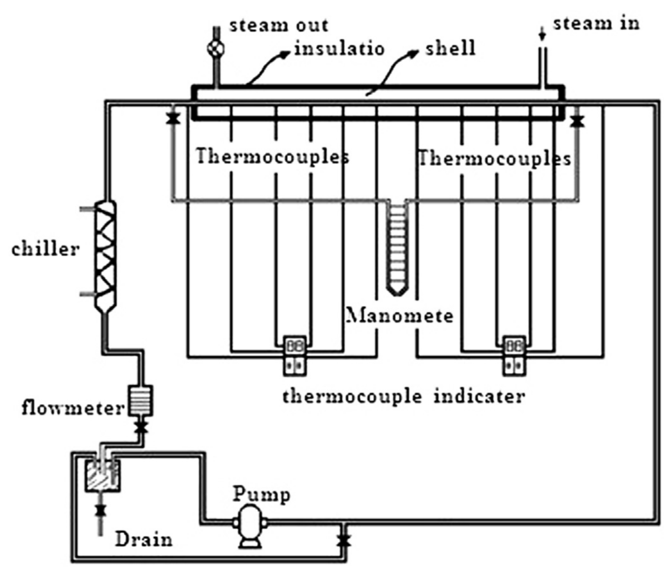

Fig. 1. Schematic of the experimental setup of [26].

Table 2
The heat transfer enhancement by a nanofluid under laminar flow [96].

Ref.	Nanofluid	*Re*	Nu_{nf}/Nu_f
Lee and Choi (1996)	Cu–water 2 vol%	Laminar	100%
Li and Xuan [7]	Cu–water 0.3–2 vol%	800–23,000	60%
Xuan and Li (2003)	Al_2O_3–water 0.2–1.6%	Laminar	30%
Yang et al. [33]	Al_2O_3–water 0.2–2.5 vol%	650–2050	350%
Heris et al. [34]	Titanium nanotube–water	110	Enhancement of *a* with *u* and Pe
Chen et al. (2008)	(aspect ratio = 10) 0.5–0.5%	700–2050	Increases with aspect ratio (nanoparticle shape) increase
Rea et al. [62]	Al_2O_3–water 0.6–6.0 vol% ZrO_2–water 0.32–3.5 vol%	1700	No abnormal heat transfer enhancement using measured properties of the nanofluid
Hwang et al. [24]	Al_2O_3–water 0.01–0.3 vol%	Laminar	+8% at 0.3 vol%
Mansour et al. (2011)	Al_2O_3/water nanofluids	550–800	Heat transfer enhancement
Sharifi et al. [32]	Al_2O_3/water nanofluids	Laminar	Heat transfer enhancement
Suresh et al. [32]	Al_2O_3–Cu/water hybrid	Laminar	Enhancement of 13.56% in Nusselt

3.1.2. Laminar flow with twisted tape inserts in a tube

Fully developed laminar convection heat transfer and friction factor characteristics of different volume fractions of Al_2O_3 nanofluid in a straight tube with different twist ratios of twisted tape inserts have been investigated experimentally by Sundar and Sharma [36]. The schematic of the test rig is shown in Fig. 2. The results showed that the heat transfer coefficient of the nanofluid was higher than the water; however, the pressure drop increases slightly with the inserts.

3.1.3. Turbulent flow in a tube

The convection heat transfer of a nanofluid through a circular tube under turbulent flow with Reynolds numbers ranging up to 2300 is summarised in Table 3. Many researchers used the Dittus–Boelter Eq. (7) for pure water as follows:

$$Nu = \frac{h_f}{k_f} d = 0.023 Re^{0.8} Pr^{0.4} \tag{7}$$

The reason for using this equation is to verify all of the results from the experimental setup before adding nanoparticles. The experimental study of the heat transfer of Al_2O_3 and TiO_2 in water through a heated horizontal straight tube has been conducted by Pak and Cho [9].

The correlation equation of enhanced heat transfer was found to be

$$Nu = 0.021 \times Re^{0.8} \times Pr^{0.5} \tag{8}$$

Li and Xuan [37] concluded that the Nusselt number of a nanofluid with a 2% volume fraction of Cu in water was 60% higher than water. The Dittus–Boelter Eq. (7) was not valid for the prediction of the Nusselt number of different volume concentrations of nanofluids. Therefore, new heat transfer correlations were established for the prediction of the Nusselt number of nanofluids flowing in a tube based on experimental data as follows:

$$Nu = 0.4328(1.0 + 11.285\phi^{0.754} Pe^{0.218}) Re^{0.333} Pr^{0.4} \tag{9}$$

$$Nu = 0.0059(1.0 + 7.6286\phi^{0.6886} Pe^{0.001}) Re^{0.9238} Pr^{0.4} \tag{10}$$

The correlation of the friction factor used for more accurate predictions might be determined by the Blasius Eq. (11a) and from

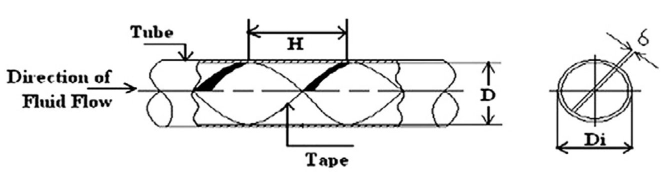

Fig. 2. Full-length twisted tape inserted inside a tube [36].

the pressure drop with the following equation:

$$f = \frac{0.316}{Re^{0.25}} \tag{11a}$$

$$f = \frac{\Delta P \times d}{L} \frac{2g}{u^2} \tag{11b}$$

The heat transfer of the nanofluids inside a tube evaluated experimentally as

$$Q = m^{\bullet} \times Cp \times (T_{\text{out}} - T_{in}) \tag{12}$$

An experimental study of the effect of nanoparticle volume fraction on the convection heat transfer characteristics and pressure drop of TiO_2–water nanofluid was conducted by [38–42]. This study demonstrated that by increasing the Reynolds number or nanoparticle volume fraction, the Nusselt number also increases. On the other hand, using a nanofluid with a high Reynolds number requires more power than one with a low Reynolds number. This power compensates the pressure drop of nanofluid. The correlation equation of the friction factor and the Nusselt number developed by Duangthongsuk and Wongwises [43] is

$$f = 0.961 \times \phi^{0.052} \times Re^{-0.375} \tag{13}$$

$$Nu = 0.074 \times Re^{0.707} \times Pr^{0.385} \times \phi^{0.074} \tag{14}$$

An experimental study of the turbulent convective heat transfer behaviour of alumina and zirconia nanoparticle dispersions in water inside a horizontal tube was conducted by Williams et al. [10]. The experimental data for single-phase convection heat transfer and viscous pressure loss correlations for fully developed turbulent flow are compared with Dittus–Boelter and Blasius equations, respectively. There was no abnormal heat transfer enhancement observed. The convective heat transfer and friction factor of Al_2O_3–water nanofluids in a circular tube with a constant wall temperature under turbulent flow conditions were investigated experimentally by [44]. The results showed that the heat transfer coefficient of the nanofluid was higher than that of the base fluid and increased with the particle concentration. Moreover, the Reynolds number had little effect on the heat transfer enhancement. The effect of the alumina nanoparticle size on the thermophysical properties, heat transfer performance and pressure loss characteristics of Aviation Turbine Fuel (ATF)-Al_2O_3 nanofluids were studied experimentally by Sonawane et al. [45]. The alumina particles with mean diameters of 50 nm or 150 nm were dispersed in ATF at 500 °C and 0.3% particle volume concentration. The results showed the heat transfer performance and pressure loss characteristics at the same pumping power; the maximum enhancement in the heat transfer coefficient at 500 °C and 0.3% concentration was approximately 47% using bigger particles, whereas it was only 36% using smaller particles. The effect of the

Table 3
The heat transfer enhancement by a nanofluid under turbulent flow [97].

Ref.	Nanofluid	*Re*	Nu_{nf}/Nu_f
Pak and Cho [9]	Al_2O_3–water TiO_2–water 3%	Turbulent	3% to 12%
Asirvatham et al. (2009)	CuO–water	Turbulent	8% enhancement
Duangthongsuk and Wongwises [43]	TiO_2/water nanofluids	Turbulent	Heat transfer is 26% greater than that of water
Vajjha et al. [67]	0.2 to 2.0% by vol.	Turbulent	Heat transfer coefficient and friction factor increased with increasing volumetric concentration of the nanofluids
Sajadi and Kazemi [47]	Al_2O_3/water nanofluids	Turbulent	Nusselt number and pressure drop increased
	CuO/water nanofluids	Turbulent	
	SiO_2/water nanofluids	Turbulent	
Akbari et al. [53]	TiO_2/water nanofluids	Turbulent	Heat transfer enhancement
	0.2 to 0.25% by vol.	Turbulent	

mean diameter of nanoparticles on the convective heat transfer and pressure drop of TiO_2–water has been studied experimentally by Abbasian [46]. The particles of size diameters of 10, 20, 30 and 50 nm were dispersed in distilled water at volume fractions of 0.01 to 0.02. The Nusselt number was compared to the base fluid, and it did not increase by decreasing the diameter of nanoparticles. The results showed that nanofluids with a 20 nm particle size diameter had the highest Nusselt number and pressure drop in the same range of Reynolds number and volume concentrations as shown in Fig. 3. A comparison of the experimental data of the Nusselt number with the existing convective heat transfer correlations is shown by Sajadi and Kazemi [47] in Fig. 4.

3.1.4. Turbulent flow with twisted tape inserts

The effect of the volume fraction of water–Al_2O_3 on the Nusselt number and friction factor in a circular tube with a twisted tape under turbulent flow has been studied by Sundar and Sharma [48]. Their results provided the heat transfer enhancement with the Reynolds number and the volume fraction of nanoparticles in water. In addition, the comparison with other researchers showed good agreement.

3.2. Numerical studies

3.2.1. Laminar flow in a tube

A numerical study was conducted by Hyder et al. [49] for Al_2O_3, CuO and TiO_2 nanoparticles in water under laminar flow in a circular tube. It predicted that the pressure drops and Nusselt number increases with increasing of volume fraction and Reynolds number. Additionally, a comparison of the numerical results with experimental data is available and there was good agreement between them.

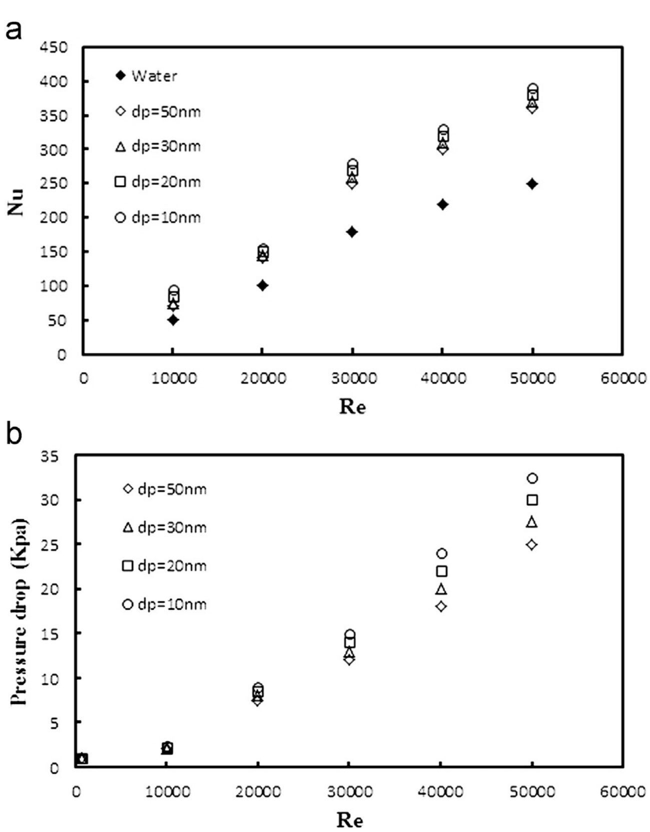

Fig. 3. The effect of size diameter on the Nusselt number and the pressure drop by [46].

3.2.2. Laminar flow in a tube with inserts

Siva and Sivashanmugam [50] numerically solved the governing equations for heat transfer of nanofluids inside a circular tube with helical inserts under laminar flow. The results showed that the heat transfer increases with the Reynolds number and with decreasing twist ratio with a maximum at 2.93. Additionally, a comparison of the heat transfer rates of water and nanofluids showed an increase in the Nusselt number of 5–34% for different twist inserts and different volume concentrations.

3.2.3. Turbulent flow in a tube

A number of investigators have studied the heat transfer and the pressure drop in a circular tube numerically [51–55]. A mathematical formulation and numerical method to determine the forced convection heat transfer and wall shear stress for the laminar and turbulent regions of Al_2O_3–water and Al_2O_3–ethylene glycol inside a uniform heated tube was introduced by Maiga et al. [56]. For the turbulent flow region, the averaged Reynolds number under the Navier–Stokes equation and the k–ε turbulent model were adopted to describe the shear stress and heat flux of the nanofluids. The grid size that was determined to be appropriate for this problem is shown in Fig. 5. In the area of laminar flow, the Reynolds number was fixed at 250 with different heat flux from 10 to 250 W/m^2. For turbulent flow, the constant heat flux was 500,000 W/m^2 and the Reynolds number varied in the range of 1×10^3–5×10^4. Fig. 6 shows the effect of the particle volume fraction on the heat transfer coefficients for both ethylene glycol and water as base fluids. They reported that ethylene glycol was better than water in hydrodynamic and heat transfer enhancement. The numerical results indicated that the heat transfer and the wall friction of nanofluids increased with increasing particle fraction and that the Al_2O_3–ethylene glycol gave a greater heat transfer enhancement than the Al_2O_3–water. For the turbulent flow region, the heat transfer performance of the nanofluids was

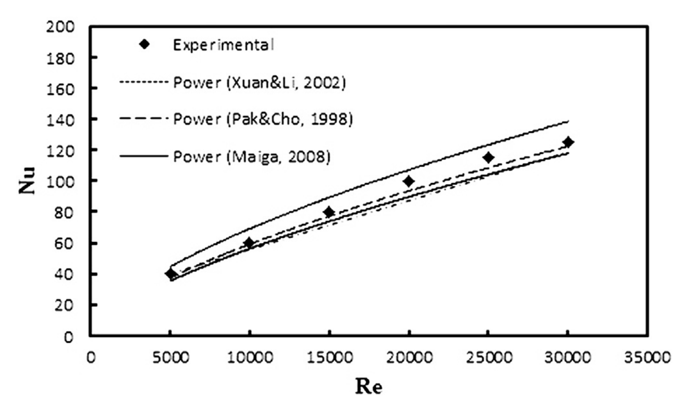

Fig. 4. Comparison of the experimental Nusselt number with existing convective heat transfer correlations at 0.2% volume fraction [47].

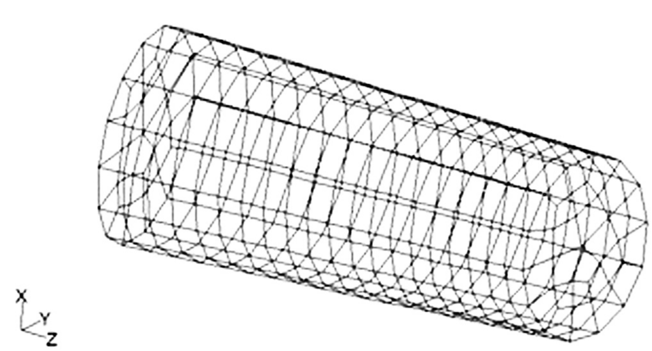

Fig. 5. Configuration of the problem in the study of [56].

more pronounced with the increase of the Reynolds number. A theoretical model of turbulent flow in a tube was proposed by [23] to predict the friction factor and the heat transfer for a wide range of nanofluids containing Cu, CuO, TiO_2, SiC, ZrO and Al_2O_3 nanoparticles of different sizes, concentration and temperatures dispersed in water. There was good agreement between the prediction values and the experimental data in the literature. Fully developed forced convection of a nanofluid (water–Al_2O_3) was studied numerically by Mirmasoumi and Behzadmehr [57]. The results showed that the convection heat transfer coefficient significantly increases with decreasing mean diameter of the nanoparticles; in addition, the hydrodynamics parameters do not change significantly. A simulation study of convection heat transfer enhancement in a circular pipe under turbulent flow was performed by Kumar et al. [58]. Forced convection under turbulent flow of an alumina nanofluid in a circular tube with a constant and uniform wall temperature was studied numerically by Bianco et al. [59]. These authors found that the nanofluid's convective heat transfer coefficient was greater than that of water. The results showed that the heat transfer enhancement increased with the Reynolds number and the volume fraction of the nanoparticles. Additionally, the friction factor and heat transfer coefficient results agreed with [9].

4. Forced convection heat transfer in a heat exchanger

4.1. Experimental studies

Many papers have focused on heat exchanger applications with nanofluids because of the wide range of applications for heat exchangers in the practical and industrial fields [60–69]. Forced convection heat transfer in a double pipe with turbulent nanofluid flow and plate heat exchangers was studied experimentally by Zamzamian et al. [70]. The nanofluid consisted of aluminium oxide and copper oxide in ethylene glycol separately. The effects of volume fraction and operating temperature on the forced convection heat transfer coefficient of the nanofluids were evaluated. The results showed that the heat transfer coefficient of the nanofluid increased with increasing nanoparticles fraction and the temperature of the nanofluid.

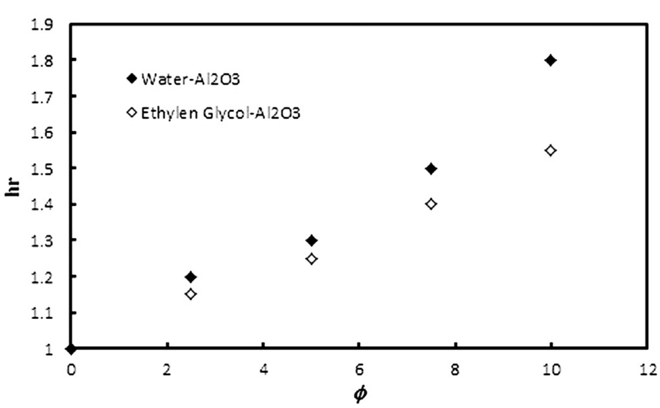

Fig. 6. Effect of the particle volume fraction on heat transfer coefficient ratios [56].

4.2. Numerical studies

Computational and numerical studies of nanofluid applications of heat exchangers were performed by [71–79]; all of them concluded that the heat transfer was enhanced in the heat exchanger when the solid particles were suspended in a base fluid. The potential mass flow rate reduction in an exchanger with a given heat exchange capacity using Al_2O_3–water nanofluids was studied by Bozorgan et al. [80]. The numerical study focused on turbulent flow in a horizontal double-tube counter flow heat exchanger. The results showed that the nanofluid flow rate decreased as the volume fraction in the exchanger increased; on the other hand, the pressure drop of the nanofluid was slightly higher than that of water and increased with the increase of volume concentration. The louvered strip inserts in a circular double pipe heat exchanger were studied numerically by Mohammed et al. [81]. The finite volume method (FVM) was used to solve the governing equations and determine the thermal and flow characteristics. Four different types of nanoparticles, Al_2O_3, CuO, SiO_2, and ZnO with different nanoparticle diameters and different volume fractions in the range of (20–50 nm) and (1–4%), respectively, were dispersed in water. The numerical results found that the heat transfer increased by approximately 367% to 411%, but the friction factor of the enhanced tube was approximately 10 times that of the smooth tube. This result indicated that the Nusselt number of the SiO_2 nanofluid had the highest value, followed by Al_2O_3, ZnO, and CuO when compared with pure water. The results showed that the Nusselt number increased with decreasing nanoparticle diameter, and it increased slightly with increasing volume fraction the streamline and isothermal line, as shown in Fig. 7.

5. Forced convection heat transfer in other shapes of tubes

5.1. Experimental studies

Because of the pressure drop limitations, the need for noncircular ducts arises in many heat transfer applications according to Tauscher and Mayinger [82]. A study of the forced convection heat transfer and friction factor in the laminar to turbulent transition region of a vertical heated rectangular channel was conducted

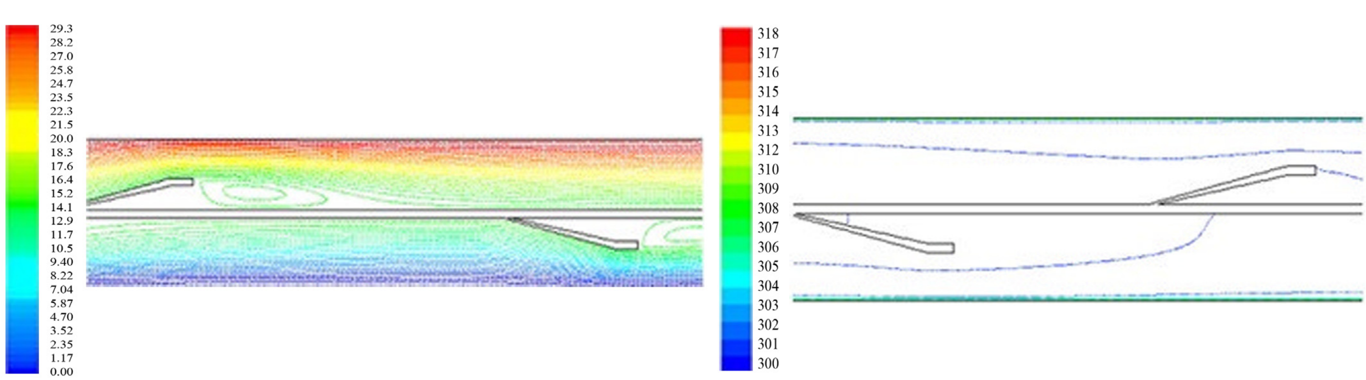

Fig. 7. Streamline and isotherms of the forward louvered strip [81].

experimentally by Wang et al. [83]. The effect of the Prandtl number on the heat transfer and friction factor was analysed in the transition region in seven groups of experiments performed in the Reynolds number range of 1000 to 20,000. The results showed that the friction factors increase with increasing Prandtl number for a fixed Reynolds number in the transition region. In addition, the comparisons between the present experimental data and classical correlations were indicated based on the experimental data. The empirical correlations for the calculation of the friction factor and the heat transfer coefficient in the rectangular channel flow transition region during forced circulation were developed. Sasmito et al. and Castiglia et al. [84,85] present studies of forced convection heat transfer enhancement by nanofluids in a helical tube. An experimental study of turbulent pressure drop and heat transfer in corrugated tubes to find the effect of SiO_2–water nanofluid have been performed by Darzi et al. [86]. The experimental work setup included a straight tube and five roughened tubes with different corrugation pitches. They obtained a correlation for the Nusselt number depending on the Reynolds number, Prandtl number and height of corrugation and pitch, which is expressed as

$$Nu = 44.26\left(\frac{e}{d}\right)^{0.89}\left(\frac{P}{d}\right)^{-0.96}(Re - 1500)^{0.27}Pr^{-0.26} \quad (15)$$

5.2. Numerical studies

A simulation study of laminar forced convection between two parallel plates with a new model including a bi-partitioned solution domain was introduced by Zhou et al. [87]. One section of the solution domain was modelled with bright meshes to solve the multicomponent flow and the other had a coarse mesh to characterise the single component flow as shown in Fig. 8. It seems that the validity and accuracy of this model compared well with LBM using only one type of modelling for the entire flow. Laminar convection under constant heat flux boundary conditions using the finite volume method to find the effects of the solid volume fraction on thermal and hydraulic behaviours of nanofluid flow in elliptical ducts have been presented by [88–90]. The results showed that for a given Reynolds number (Re), the Nusselt number (Nu) increased with the volume fraction of solid nanoparticles while the friction factor decreased. The effect of aspect ratio (b/a) in elliptic tubes reduced the local friction factor, whereas it had no effect on the local Nusselt number. The laminar flow forced convection heat transfer of a CuO–water nanofluid in a triangular duct under a constant wall temperature condition was investigated numerically by Heris et al. [91]. This study evaluated the effect of the nanoparticle volume fraction, size diameter, and type on heat transfer and compared the results between the nanofluid and the pure fluid. A comparison of the convection heat transfer of a nanofluid in isosceles triangular ducts with various apex angles was also presented. The results showed that an equilateral triangular duct has a maximum heat transfer compared with other types of isosceles triangular ducts. A numerical study of the heat transfer enhancement by internal longitudinal ribs and alumina water nanofluid in a stationary curved square duct was performed by Soltanipour et al. [92].

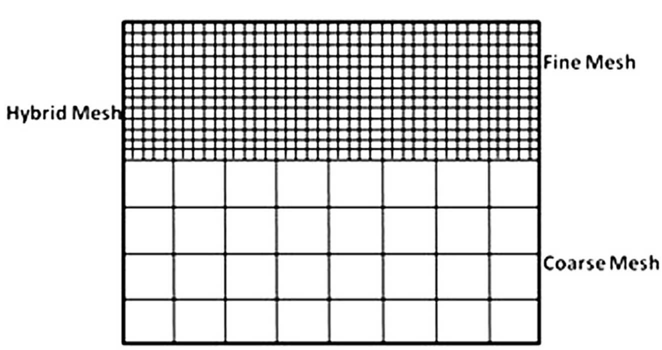

Fig. 8. Different regions of meshing for a Couette flow [87].

The geometry of a ribbed curved duct and the coordinate system assumed constant properties: laminar, three-dimensional flow, steady, and incompressible. The governing equations were solved with the finite volume method. The effects of the Dean number, rib size and volume concentration on the coefficient of heat transfer and pressure drop were measured.

$$De = Re\sqrt{\frac{D_h}{R}} \quad (16)$$

Numerical results showed that the heat transfer coefficient increased with increasing nanoparticle concentration. Additionally, the addition of a nanoparticle to the base fluid is more useful for low Dean number. In the case of water flow, results indicate that the ratio of heat transfer rate of a ribbed duct to a smooth duct is nearly independent of Dean number (De). Fig. 9 shows the effect of the particle volume fraction on the heat transfer and pressure drop ratio in a ribbed curved duct. The forced convection heat transfer of a nanofluid under laminar and turbulent flow through a finned tube was studied by Pongsoi et al. [93].

6. Experimental and numerical studies

Numerical simulation and experimental investigation of laminar forced convection heat transfer of an Al_2O_3–water nanofluid was introduced by Sharifi et al. [94]. Depending on the temperature, the single phase model was employed in the numerical simulation of

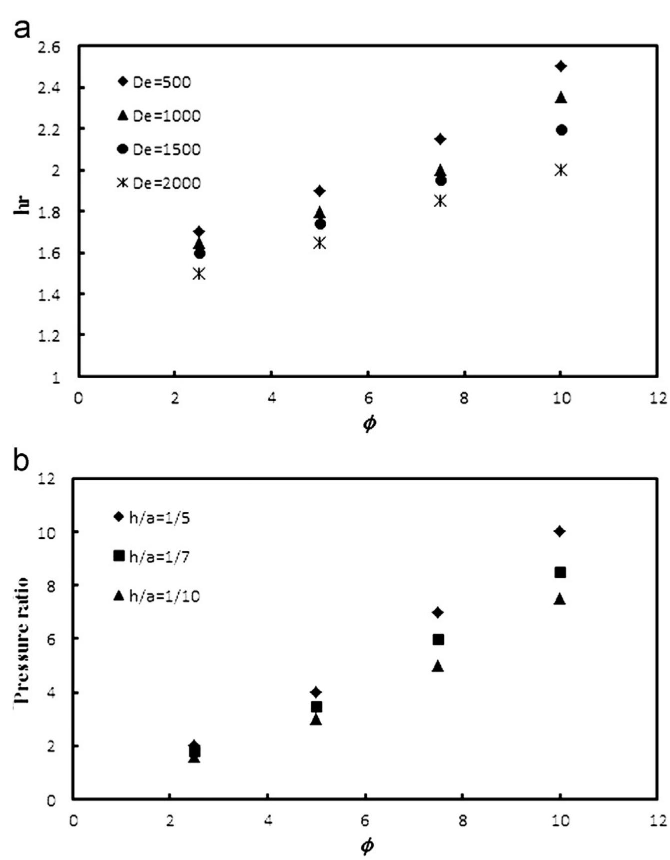

Fig. 9. The effect of the particle volume fraction on: (a) the heat transfer coefficient ratio with Dean number and, (b) the pressure drop ratio in a ribbed curved duct [93].

the nanofluid transport phenomena and grid meshing was used in the numerical part. Experimental and simulation results indicated good enhancement of convection heat transfer of the base fluid by adding small amounts of Al_2O_3 nanoparticles to the base fluid. The heat transfer was enhanced with increasing nanoparticle concentration and the Reynolds number of flow, as shown in Fig. 10. Additionally, the contour of temperature and velocity with tube length is shown in Fig. 11.

7. Outlook

Regarding all of these papers describing experimental studies, the heat transfer in a fluid may be enhanced with suspended small solid metal or non-metallic particles less than 100 nm in diameter, even with a small percentage volume fraction. Meanwhile, the numerical studies using commercial simulation software show enhanced heat transfer in fluid through a circular tube, a heat exchanger and tubes of other shapes. The author will focus on heat transfer enhancement by adding a high volume fraction of solid particles to water experimentally. Additionally, numerical studies of heat transfer enhancement using CFD commercial FLUENT software compared with experimental data and correlated equations of the Nusselt number and friction factor in an automobile radiator cooling system would be useful. In addition, the tube shape of a car radiator is represented as a flat tube, so a comparison among other shapes (e.g., circular, flat and elliptical tubes) will be necessary in future studies. The type of nanofluid in these literature studies are metallic or non-metallic nanoparticles suspended in a base fluid, but the author will prepare hybrid nanofluids suspended in mixed base fluids to enhance the heat transfer of an automotive cooling system.

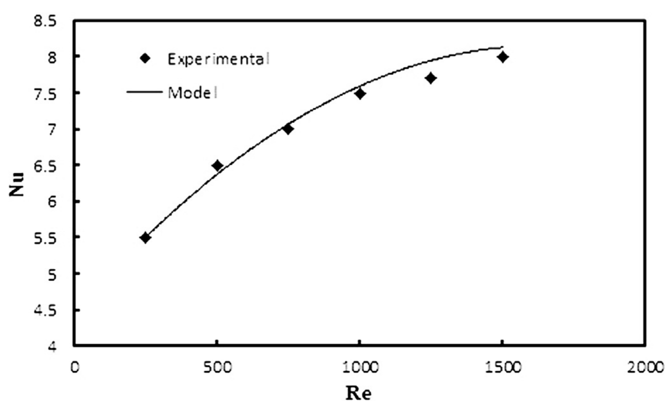

Fig. 10. The effect of the nanofluid flow Reynolds number on the Nusselt number at a concentration of 5% by vol. of Al_2O_3 nanoparticles [94].

8. Future work

It is necessary to study how to develop correlations of friction factor and heat transfer through tubes filled with nanofluids. Hence, further studies are needed to develop generalised hydrodynamic and heat transfer characteristic correlations for nanofluid in a tube. Furthermore, the effect of the tube shape (e.g., flat, elliptical or circular) on the hydrodynamics and heat transfer in a tube and heat exchanger need to be understood. Additionally, a comparison among tube shapes for use in a car radiator can be performed experimentally and numerically. High volume concentrations of various types of nanofluids may be used as a coolant in a car radiator. A hybrid nanofluid prepared from mixing types with same volume fraction can be studied in the future for augmentation of the heat transfer and friction factor. Additionally, the mixing of base fluids can be used in an automobile radiator to enhance the heat transfer and hydrodynamic characteristics as future work.

9. Conclusions

Nanofluids are a new class of heat transfer fluid engineered by dispersing metallic or non-metallic nanoparticles less than 100 nm in size in a liquid. The thermal properties of solid nanoparticles give the base fluid better hydrodynamic and heat transfer attributes. The great potential of nanofluids for heat transfer enhancement in highly suited practical heat transfer applications will lead to the development of compact and effective heat transfer equipment by engineers. The enhanced heat transfer potential of the base liquids will offer an opportunity for engineers to develop highly compact and effective heat transfer equipment for many industrial applications, including transportation, nuclear reactors, electronics, biomedicine, and food. According to the majority of experimental and numerical studies, suspensions of solid nanoparticles significantly enhance heat transfer and the heat transfer coefficient of nanofluids is found to be larger than that of its base fluid at the same Reynolds number. Additionally, increasing the volume fraction of solid nanoparticles increases the heat transfer of nanofluids. On the other hand, the friction factor and pressure drop of nanofluids are larger than the base fluids. The enhancement of the heat transfer of the nanofluids may be caused by the suspended nanoparticles increasing the thermal conductivity of fluids, and the chaotic movement of ultrafine particles increases fluctuation and turbulence of the fluids, accelerating the energy exchange process. Furthermore, the numerical correlations of

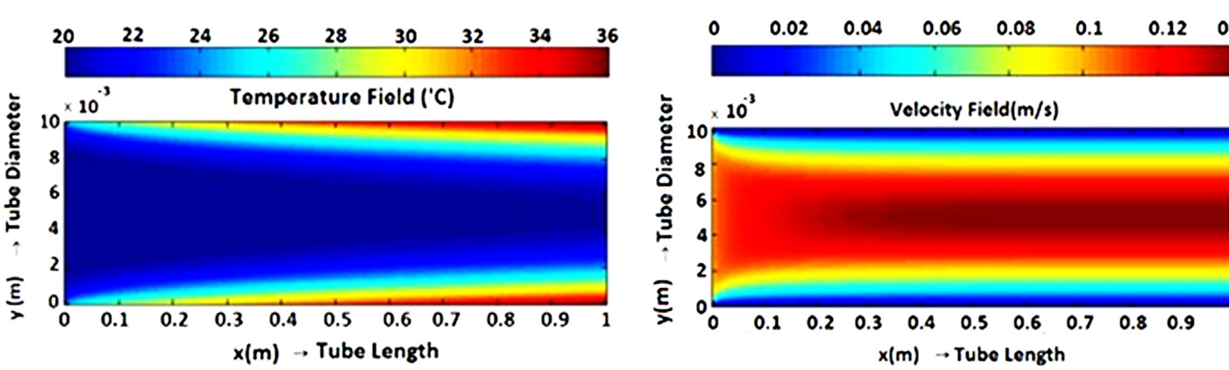

Fig. 11. (a) The temperature field of nanofluid flow (b) the velocity field of nanofluid flow, at $Re = 1000$, 5% by vol. of Al_2O_3 nanoparticles and heat flux $= 5000$ w/m^2 [94].

single-phase fluid have clearly failed to predict the heat transfer coefficients of nanofluids. The Nusselt number is predicted for the different volume concentrations of nanofluids in a circular tube as in Eq. (7) for laminar and Eq. (8) for turbulent, and the correlation of friction factor is used for more accurate predictions in Eq. (9). The relationships among the Nusselt number, the Reynolds number, the Prandtl number, and the height of corrugation and pitch has been correlated in Eq. (15).

Future studies are very important for determining a plan of research and any work that will be proposed. It is necessary to study the development of correlations of friction factor and heat transfer through tubes with nanofluids. Hence, further studies are needed to develop a generalised hydrodynamic and heat transfer characteristic correlation for nanofluid in a tube. Furthermore, the effect of the tube shape (e.g., flat, elliptical or circular) on the hydrodynamics and heat transfer in a tube and heat exchanger are needed. Additionally, a comparison among tube shapes for use in a car radiator can be performed experimentally and numerically. High volume concentrations of various types of nanofluid may be used as coolant in a car radiator. The hybrid nanofluid prepared from mixing types with the same volume fraction can be studied in the future for augmentation of the heat transfer and friction factor. Additionally, the mixing of base fluids can be used in an automobile radiator to enhance heat transfer and hydrodynamic characteristics as future work.

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